K-045 E

UNITED NATIONS

ECONOMIC AND SOCIAL COUNCIL

CES/AC.56/4
WATER/AC.5/R.3
21 October 1981

Original: ENGLISH

STATISTICAL COMMISSION and ECONOMIC COMMISSION FOR EUROPE
CONFERENCE OF EUROPEAN STATISTICIANS

ECONOMIC COMMISSION FOR EUROPE
COMMITTEE ON WATER PROBLEMS

Meeting on Statistics of Water Use and Quality
(18-21 January 1982)

FROM WATER QUALITY TO THE ECOSYSTEM CONCEPT: EXPERIENCE GAINED FROM A CASE STUDY OF THE STRESS RESPONSE ENVIRONMENTAL STATISTICAL SYSTEM AS APPLIED TO THE LAURENTIAN LOWER GREAT LAKES

Submitted by Statistics Canada 1/

INTRODUCTION

1. In recent years Statistics Canada developed a provisional framework for environmental statistics. This framework, the Stress Response Environmental Statistical System (STRESS) is a system for integrating information on stress on the environment from human activities, environmental transformation, social and economic impacts and individual and collective responses.

2. The ecosystem approach, as embodied in STRESS, and in the various efforts to rehabilitate and restore the Great Lakes (by efforts of the International Joint Commission, the Great Lakes Fisheries Commission, the Great Lakes Basin Commission) requires a shift of perspective from the approach of the economist and engineer to that of the ecologist-one that views the aquatic system as not only a chemical system receiving point source effluents, but a highly complex system integrating loadings from waste residuals through air and drainage basins, and stresses of other sorts such as overharvesting, physical restructuring and the like.

3. Traditionally the statistical universe of the Bureau has been in the socio-economic field. However, it is now generally recognized that this statistical "cosmology" is incomplete. The environmental dimension is simply missing. As the limits and tolerances of the natural systems to stresses from human activities are approached or exceeded, it is likely that the need for environmental statistics will become quite significant. The development work within the Bureau has thus been directed towards a search for appropriate frameworks to guide the expected developments in this new statistical field.

4. STRESS, the framework to be discussed in this paper, is an ecosystem based approach to environment. In contrast to classification of environment by the traditional categories of air, water and land, the ecosystem approach is regionally focussed and conceptually a holistic integrated approach - recognizing explicitly the linkage among the biotic and abiotic components of the natural system.

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GE.81-33203

5. Ecosystems, just as economic systems, are inherently so complex as to be intractable to our capability for understanding. However, as in economic analysis, if a comprehensive framework for analysis is first established, it is possible to intelligently isolate aspects of the system most relevant to the problem at hand. What is required is a statistical taxonomy for environment which brings together the major dimensions of stress on the environment and environmental responses. In this task, water quality aspects (as traditionally defined) require reconsideration in order to provide information on the many services provided by aquatic systems.

6. To better assess the strengths and weaknesses of the STRESS system Statistics Canada carried out, as an illustrative example, a study of transformation in the Laurentian Lower Great Lakes. The focus was on transformation in the aquatic ecosystems of Lakes Erie and Ontario, as affected by activities in the lake basins and the surrounding drainage basin. The specific goals were:

(a) to determine the extent to which available data satisfied the information needs of STRESS;

(b) to examine the quality of the data--particularly on the environmental response side, an area the Bureau has not had prior experience with;

(c) to assess the prospect or potential for development of macro environmental statistics from the local monitoring data. In this connection temporal and spatial limitations to aggregation of environmental data were of interest;

(d) to evaluate STRESS in terms of the adequacy of its taxonomy for environmental data. To what degree could the taxonomy accommodate the numerous specific types of stress data and response data pertaining to the Lower Great Lakes?

7. The case study, while having the above noted goals, has by its nature considered questions germane to the development of classifications for water quality. Traditional water quality data may be used as proxies for important functional aspects of ecosystems. However, the ecosystem approach places emphasis on indicator and integrator measures which use the biota to reflect environmental transformation. In this aspect, new sorts of "water quality" data are required--from an ecological perspective, as well as from a chemical, engineering perspective. (paragraphs 26-32)

8. In the case study, water was considered as an amenity for human consumption, in terms of its aesthetic and recreational potential and also as essential habitat for renewable resources--particularly fish. In these aspects, too, new dimensions to traditional water quality statistics should be considered. (paragraphs 33-38)

9. Our approach in the present paper will be to draw from the case study those aspects that have a bearing on the possible broader considerations of water quality, as they have emerged in recent efforts to rehabilitate the Great Lakes,

An Overview of Transformation in the Lower Great Lakes

10. In the course of two centuries of stress on the Lower Great Lakes Drainage Basin, the environment of this region has altered drastically. The virgin forests are almost entirely gone (which for Lake Erie consisted of large stands of hardwoods, with a million acre wet forest at the south-west corner), and also gone are the vast savannahs of grass and wild oats, often two to three meters high. This abundant vegetation, historically limited soil erosion, and consequently most streams feeding the Lower Lakes were clear and cool and free of clay and silts. With land clearing for agriculture, there was a dramatic increase in the silt in rivers which had the effect of spoiling much of the breeding grounds of valued fish species, such as walleye and lake whitefish. Drainage of most of the swamp areas further decreased fish habitat, as did the construction of numerous mills and dams.

11. In historic times, the water quality of the Lower Lakes resembled somewhat that of the Upper Lakes today, that is it was relatively clear, of very low nutrient content and supported relatively little algae. This was the habitat suitable for large and valued fish species. Today the conditions of the Lower Lakes are organically enriched, highly turbid and support luxuriant algal blooms--all to the detriment of preferred fishstocks, and to various recreational uses of these waters.

12. The fish community has been further stressed by overharvesting, despite efforts at regulation, and also by the accidental introduction of non-native species--particularly the escape of the sea lampray via the Welland Canal from Lake Ontario into Lake Erie. Fish associations in the Lower Lakes in the early 1800's were comprised of relatively large size species, such as sturgeons, lake trout, lake whitefish, northern pike, muskellunge, walleye, etc. and in Lake Ontario, Atlantic salmon. It has been suggested that perhaps 50% of all the fish biomass in these waters consisted of individuals greater than 5 kilograms in weight. In contrast, today, the bulk of the fish community is comprised of relatively small fish, such as smelt and alewife. There are a large number of native fish that have become extinct and a large number of exotic fish, such as brown trout, Pacific salmon, rainbow trout, rainbow smelt, alewife, goldfish and carp that have increased in abundance.

13. Microcontaminants pose another threat to the lakes. This problem is far less of a problem for the fish in the lakes than it is for the human beings that live in the drainage basin.

14. The combined effect of these various stresses, (waste residuals, physical restructuring, harvesting, exotics, climatic factors) has been to drastically alter the character of the Lower Lakes.

From Water Quality to an Ecosystem Approach: A Shift in Perspective with Respect to Rehabilitation of the Lower Great Lakes

15. In 1972 the governments of Canada and the United States entered into an Agreement with respect to water quality of the Great Lakes. In 1978 the Agreement was renegotiated and the new terms reflect a recognition of the limitations of the water quality concept as conventionally defined, and the recognition of the necessity of moving towards implementation of an ecosystem concept. Water itself is no longer viewed as a sufficient basis for maintaining "water quality", but rather "the restoration and enhancement of the boundary waters cannot be achieved independently of other parts of the Great Lakes Basin Ecosystems with which waters interact". The ecosystem approach recognizes the

importance of taking into account the entire Great Lakes drainage system--including the land that surrounds the lakes, the streams flowing into the lakes, the connecting channels as well as the Great Lakes themselves. This involves recognition of the complex interactions among water, land, air, and the biota. The new agreement requires the parties to develop remedial and preventive measures (for example to ban toxic loadings to the lakes) and other actions that require not only open-lake, water column monitoring, but also ecosystem monitoring.

16. In Article 3 of the 1978 Agreement the wording was changed to delete the terms "water quality" from the statement of "objectives" thus opening the way to broad ecosystem dimensions of the problem.

17. To change the wording of the Agreement, of course, by no means ensures that changes find their way into practice. One key difficulty is the "human factor", the individuals responsible for managing the industrial complex surrounding the Lower Great Lakes, and many of those responsible for the monitoring programs and facets of management of the Lakes bear the hallmark of their training in engineering and economics, and have little appreciation for the ecosystem perspective. It is probably the case that the ecosystem concept is not yet understood by the public or managers of the Great Lakes. Most people may associate "ecosystem" with nature conservation and fail to see direct relevance to economic and social conditions. This attitude is, of course, changing, as more publicity of the "services" that nature provides, such as dubbing the marshlands "natures kidneys" reaches the public.

STRESS: Environmental Statistics in an Ecosystem Context

Taxonomy of Stresses on the Environment

18. STRESS through its classification system, integrates data on impacts of human activities on the aquatic ecosystem, as conveyed by air, land and water. The classification adopted for the Lower Lakes Study is given below:

(a) Generation of Waste Residuals--point source and diffuse loadings of nutrients, toxins, heat, radiation, etc. into the environment. Documentation of stress from the generation of waste residuals includes traditional water quality measures, but also includes using the biota as indicators and integrators of toxic stress. Biota serve as temporal and spatial integrators of contaminants. In the Lower Great Lakes data on Herring gulls, concentrations of contaminants found in fish (with respect to mirex, PCB's, DDT, Mercury and a number of other contaminants) provides a much better integrative measure than do the open water chemical measures. Further the gulls are an example where the ecosystem concept is explicitly recognized, since gulls being land based, serve nonetheless for assessment of water quality, since via the aquatic food chain, they reflect accumulation of contaminants in the aquatic ecosystem.

(b) Permanent environmental restructuring - Direct physical alterations to environment. In the context of the Lower Lakes, drainage of wetlands, construction of dams and canals, and shoreline restructuring have been significant.

(c) Harvesting of renewable resources. Harvesting of the forests, agriculture and fisheries. The case study documents fisheries since these activities most directly alter the Lower Great Lakes Aquatic Ecosystems. The indirect effects of harvesting of agriculture and forests enter in through the accounting of generation of waste residuals and permanent environmental restructuring (for example the drainage of marshlands for agricultural use).

(d) Exotics - The purposeful or accidental introduction of non-native species.

(e) Natural Geophysical activity. Climatically, geophysically, or physically induced events, such as periodic storms, which may have significant repercussions for the biota of the lakes.

Environmental Responses

Use of Water Quality Statistics in an Ecosystem Context

19. The ecosystem health is reflected in a classification of data into three major categories:

(a) Primary productivity - or the rate of energy fixation and transfer within the ecosystem.

(b) Nutrient availability and cycling within the biotic and abiotic components of the system.

(c) The composition of the biota - both in terms of relative abundance (species dominance), and species diversity.

20. Traditional water quality data might find application in reflecting the first two of the three major ecosystem level indicators of system viability - namely the energy transformation and nutrient cycling and availability.

21. With respect to energy transformation, Great Lakes Water quality monitoring samples the ubiquitous photosynthetic pigment, Chlorophyll a, found in algae, diatoms and other aquatic plants. This measure has been taken as a proxy for primary productivity in the lakes, although strictly speaking, the measure is as best an indicator of primary biomass. However, for comparative purposes, that is to compare the relative productivity of different areas of the Lower Lakes the measure suffices in a rough sort of way.

22. The data on Chlorophyll a were found to be highly variable from year to year. This might be expected for large water bodies, where it is exceedingly difficult to time the monitoring to reflect the same stage in the seasonal cycle. The Chlorophyll a monitoring data are affected by highly variable conditions such as changes in water depth, nutrient loadings from drainage basin, water temperature, etc. - all of which have large year-to-year variability.

23. To adequately assess temporal changes in Chlorophyll a in the Great Lakes would require a considerably more intensive sampling program than currently being undertaken - perhaps with reliance of a relatively small number of near-shore stations for very intensive monitoring in order to establish temporal trends. The current data are, however, sufficient to differentiate spatially the various near-shore and offshore regions of the Lower Lakes.

24. With respect to the information required on ecosystem processing of nutrients, the monitoring data on phosphorus (thought to be the major limiting nutrient in the Lower Lakes) and nitrates, is of relevance. As in the case of Chlorophyll a, for these large water bodies, the monitoring data have proven more useful in differentiating subregions in terms of the relative degree of nutrient availability, rather than establishing trends through time. Although, recent analysis of the Lake Ontario phosphorus data does yield a slightly decreasing trend over the 1970-78 period, one that is of some interest owing to the restrictions of phosphates that were put in effect in the early part of this period. However, analysis indicates that the amount of reduction could hardly be completely explained by the restrictions on inputs, and therefore involves other aspects of the ecosystem, such as the rate of phosphate sedimentation from the water column.

25. This raises the question of the adequacy of phosphorus concentrations alone, from the ecosystem perspective. Such data, need for their proper interpretation (in an ecosystem context) to be supplemented by information on the rate of phosphorus turnover. The fact that such studies are not more prominent in the Great Lakes monitoring program reflects, to a large degree, the human factor - the engineering as opposed to ecological perspectives of those responsible for the monitoring programs.

Biotic Indicators and Integrators of Environmental Transformation

26. The biota serve not only as indicators of toxic stress on the Lower Lakes ecosystems (through bioaccumulation of toxins) but also reflect other features of water quality - since water being an important part of the habitat for the aquatic biota, changes in any one of the characteristics of this aquatic habitat may well affect the distributions of the resident biota. In this regard the biota themselves serve as data for the response side of aquatic ecosystems. In this, we differentiate between indicators which refer to sensitive species that are either permitted or excluded by environmental conditions and integrators by which we mean, in this context, changes in the diversity and composition of the biotic community. Integrators also refer to species at the top of the food chain which serve as bioaccumulators of toxic substances.

27. In the case study, benthic organisms served as indicators of organic pollution in the Lower Lakes. Data collected under the International Field Year for the Great Lakes, on the distribution of oligochaetes of Lake Ontario showed the distributions of one species (Tubifex tubifex) is highly correlated with waters adjacent to urban centers (especially Toronto and Burlington) while another species (Stylodrilus heringlanus) is conspicuous by its absence in areas near urban centers, yet this species dominates the benthic community in most other regions of the lake. Interpretations of these changes in distributions of benthos are complex, and involve the extent of nutrient and organic enrichment, the degree of anoxia in the bottom waters and other factors. The important point, however, is that the organisms themselves can serve as a measure of change in water quality and differentiate regions near human settlements from less polluted regions.

28. The survey of Lake Ontario Cladophora (a nuisance algae which results in serious degredation of nearshore areas for recreational use) is another example of the potential usefulness of indicator species. This nuisance alga first noted in the Toronto area of the Lower Lakes in the 1930's spread such that within twenty years its distribution formed a lush biomass covering most of the open wave swept shorelines of Lake Ontario. Near the Bay of Quinte, Cladophora covered, (according to a 1974 survey) some 30% of the shoreline, displacing a much more diverse community of diatoms which inhabited similar substrate.

29. Changes in the composition of fish communities reflects in an integrative manner the multiple stresses that have acted to transform the Lower Lakes.

30. One measure of the drastic restructuring of the Great Lakes fish community is to group species in terms of the habitat occupied during the mid-summer, non-breeding season. Classifying fish species into three categories - the benthic fish (comprising generally large fish restricted to near-shore and offshore bottom waters), the large pelagic fish (comprising offshore fish found in surface waters) and the small pelagic fish (comprising offshore smaller fish found in the surface waters), we compiled data on the commercial catch of fish by lake basin (separating the catch for Lake Erie into the three sub-basins - Western, Central and Eastern). In Table 1 we indicate the trend in the catch - which undoubtedly reflects, to a large degree, the basic change in available stocks of fish from dominance by the benthics, to dominance by the small offshore pelagics. (Table 1 covers Lake Ontario data only.)

Table 1: Commercial Fish Landings in Lake Ontario by Habitat and Size*

Year	Ratio Small Pelagics to Big Benthics	Ratio Small to Big Pelagics
1958	.729	4.192
1959	.524	2.904
1960	.594	3.557
1961	.537	4.510
1962	.557	2.583
1963	.715	2.416
1964	1.851	3.320
1965	4.142	7.313
1966	3.152	6.304
1967	5.257	7.519
1968	3.453	7.616
1969	4.384	9.324
1970	10.426	26.065
1971	16.913	35.364
1972	18.323	37.867
1973	16.017	24.833
1974	12.620	22.400
1975	13.700	22.216
1976	20.857	48.667
1977	16.595	58.083

* Small Pelagics comprise Smelt, Alewife, Yellow Perch. Big Benthics comprise Lake Whitefish, Burbot, Lake Trout, Sturgeon, Northern Pike, Walleye, Channel Catfish. Big Pelagics comprise Blue Pike, Lake Herring, White Bass and Sheepshead.

Source: Compiled from data on landings of species, in Great Lakes Fishery Commission Technical Report #3 and supplements.

31. Economic effects of changes in the composition of fish community are reflected in data on the percentage of the total catch comprised of "high-valued" species. "High-valued" species were defined as those species with a market price greater than the mean for all species sold in the particular year and location. We show in the Table 2 (illustrated on following page) an example of these data. Price refers to $/lb.

TABLE II. - Fish of "High Value" as Percentage of Total Landed Catch in Canadian Waters of Lake Ontario 1953-76

Year	Fish of "High Value" as Percentage of Total Landed Catch
1953	18.4
1954	21.6
1955	27.7
1956	30.9
1957	30.0
1958	32.2
1959	26.3
1960	30.4
1961	36.9
1962	29.7
1963	24.4
1964	11.6
1965	7.3
1966	8.3
1967	4.4
1968	6.2
1969	5.1
1970	2.3
1971	0.9
1972	1.2
1973	1.0
1974	1.0
1975	0.7
1976	0.3

32. In summary, the differences between the STRESS approach to environmental statistics and the more traditional "media" approach lies first in the fact that STRESS provides a framework for integrating information on human activities within a regional context and for indicating the ecosystem response to multiple stresses from human activities. Responses are not only reflected in changes in water chemistry (as these relate to aspects of productivity and nutrient cycling) but also in terms of the changes in the composition of the biota - which serve as both indicators and integrators of environmental transformation.

Integrating Water Quality and the Ecosystem Concept

33. In this section the role of water quality statistics in the ecosystem context is summarized on the basis of our experience with the Lower Great Lakes Case Study. We review the difficulties with using current water quality data for reflecting the critical aspects of ecosystem function - e.g. the productivity of the system, and the nutrient cycling capabilities. We then shift the focus from ecosystem properties to consideration of the Lakes as an amenity and as a renewable resource system for fisheries. The concept of "water quality" ought to be broadened to consider all of these dimensions of aquatic ecosystems - rather than its usual limitation to aspects relating to human consumption and industrial use of water.

34. Considering first the use of water quality statistics to document certain functional aspects of ecosystems, we observe that the "standard" water quality parameters for primary biomass, namely Chlorophyll a concentrations, and for nutrients, namely phosphorus and nitrate concentrations may serve as proxies for aspects of energy transformation and nutrients in the Lower Lakes. However, it is clear that these measures are not wholly adequate from several points of view. Firstly, the measures themselves are only a relatively crude indicator of the underlying functional properties of ecosystems, e.g. the changes in productivity, and the nutrient cycling. Secondly, owing to the extremely high natural variability in these large fresh water systems, cost effectiveness in obtaining comparable year-to-year data is rather low. This is particularly the case with Chlorophyll a data which are highly variable from year-to-year, owing to different onset of the seasonal cycle and thus it is almost impossible to time monitoring activities for peak production in the spring of each year. The problem of temporal variability is only somewhat less for the monitoring of phosphorus and nitrates, since during the period after spring overturn of the lake waters, there is relative homogeneity and stability in concentrations of nutrients in the offshore water column.

35. Water quality, in terms of the suitability of water for human consumption relies, of course, not only on the analysis of water chemistry, but also takes into account that the presence of certain indicator organisms, for example, coliform bacteria indicate pollution, from fecal contamination. The indicator approach could be further developed in classifications for water quality statistics. For example, in the Lower Great Lakes, the presence of indicator species from the Oligochaete family differentiates rather well the near-shore regions adjacent to urban centers from those not close to human settlements, since particular oligochaete species are excluded or favoured by high organic content.

36. The biota also function as integrators of chemical stress in these waters. In this regard, the concentration of toxins in fish and in herring gulls is particularly informative. The latter also is illustrative of an ecosystem perspective with respect to water quality, for in this case, the measure of water quality is indicated by concentration of toxins in a land based species.

37. Water as media for the production of fish, takes on a different hue in terms of indicators of "quality". For this purpose, the quantification of suitable fish nurseries, (e.g. the wetlands, and the various shoals and other breeding habitat of the lakes) is an indicator of water quality. In the Lower Lakes, the substantial disappearance of the marshlands over the last century has greatly reduced the quality of these waters for producing certain fish stocks. Pike and muskellunge as well as some other species spawn on flooded

wetlands and marshes. The draining of these areas and the effect on the adjacent macrophyte beds, lead to a reduction in the nursery habitat for the young of these species and have led to a decline in certain valuable stocks. Thus it is far more than water chemistry that determines the extent to which the aquatic system is able to support valued fish stocks. For the Lower Great Lakes, the disappearance of marshlands could be taken as a direct indicator of the loss of water quality in terms of its suitability for producing fish.

38. As recreational space, water quality also needs additional dimensions other than water chemistry. The distribution of the nuisance algae Cladophora, for example, in Lake Ontario conveys considerable information in terms of areas that are of unacceptable quality for their use for swimming, certain types of boating, and sports fishing. Huge mats of this algae accumulate and when they break off and get washed ashore are responsible for fowl smells from their decay - rendering beaches unsuitable for recreational use.

Summary

39. In this paper we have shown some implications of the case study on the Lower Lakes for water quality classifications. There has recently been an evolution in management approaches to these systems from water quality to an ecosystem approach. In this context conventional water quality data might be modified to reveal other properties of the system (the dynamics of energy transformation and nutrient cycling, for example). Further, considerable use might be made of biotic indicators and integrators - reflecting water quality in a conventional sense, and also reflecting new dimensions of the quality of aquatic ecosystems in terms of their capability to support their renewable resources, and be acceptable for various recreational uses.

40. The case study reveals some considerable advantages in using biotic indicators of water quality, particularly since these communities tend to be good temporal and spatial integrators, overcoming in this way the difficulties of monitoring a very "noisy" system from the standpoint of water chemistry. The high variability in the water chemistry of the large systems often precludes cost effective analysis of trends through time, and a detection of critical short lived, but potentially hazardous phenomena may better be captured in changes in component biotic communities (such as the benthos).

41. Further the case study considers water quality, not only from the point of view of human consumption and industrial use but also from the standpoint of habitat for valued fish stocks, and as habitat for recreational use. In these aspects, again, the biota are of importance in indicating water quality. Water chemistry thus needs to be supplemented by measures such as, for example, the amount of wetlands. With respect to recreation, the distribution of the algae Cladophora is of some importance in indicating regions of the near-shore zone that are of unacceptable quality for recreational use.

42. Further work on frameworks for water quality classifications ought to give more explicit recognition to water in the ecosystem context, and more specifically consider the use of biota as sensitive indicators and integrators of the quality of aquatic environments from the amenity, ecosystem and renewable resource perspectives.